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ORIGINAL ARTICLE

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Bending creep of glued laminated timber (glulam) using sugi (*Cryptomeria japonica*) laminae with extremely low Young's modulus for the inner layers

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Abstract The main purpose of this study was to establish whether sugi lumber with an extremely low Young's modulus, which is plentifully produced in southern Japan, can be practically used as laminae for glued laminated timber (glulam) from the viewpoint of long-term performance under loading. Bending creep tests were carried out on sugi (*Cryptomeria japonica* D. Don) glulam with extremely low Young's modulus laminae (3–4 kN/mm^2) for the inner layers, as were tests on hybrid glulam with Douglas-fir (*Pseudotsuga menziesii* Franco) laminae (14–15 kN/mm^2) for the outermost layer and sugi laminae (including those with a Young's modulus of 3–4 kN/mm^2) for the inner layers. The specimens were eight glulam beams with different compositions that were 105 mm wide, 210 mm deep, and 3980 mm long. The term of the creep test was 4 years. The results are summarized as follows. First, there were no significant differences between the Young's modulus or bending creep of glulam L30 (laminae with Young's modulus of 3–4 kN/mm^2) and that of glulam L50 (laminae with Young's modulus of 5–6 kN/mm^2) for the inner layers. Second, for asymmetric compositions, the behavior of increases and decreases of relative creep due to atmospheric changes showed opposite behavior for glulam loaded from the side of lower Young's modulus and from the side of higher Young's modulus. Third, the required experimental term for the creep test to estimate an accurate long-term curve is 1 or 2 years (with data for the first 6 months excluded) when the power law is used for the estimation. Fourth, the values of relative creep in 50 years obtained from the experimental term were much lower than 2, which is the standard value set by Notification No. 1459 of the Ministry of Construction in Japan, and these values were not affected by the composition of the laminae.

Key words Creep · Mechanosorptive deflection · Power law · Sugi · Glulam

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Introduction

Glued laminated timber (glulam) used in Japan is mainly applied as columns and beams of wooden houses by the conventional Japanese construction method, whereas it used to be used as a structural material for large-scale buildings. However, 90% or more of glulam is imported or is composed of imported laminae,[1] and the ratio of domestic laminae used in glulam is very low under present conditions. This situation resulted from the Japanese Agricultural Standards (JAS) for glulam that set the guidelines for glulam to compete with steel for strength in large-scale construction.[2] In particular, Japanese cedar (*Cryptomeria japonica* D. Don), known locally as sugi, was considered to be unsuitable for use as laminae because of its low strength and Young's modulus. In order to make glulam composed of sugi laminae a useful and reliable option, it is imperative to develop standards for glulam with adequate data based on realistic conditions.

Against this background, Japanese researchers carried out joint research to ascertain whether domestic glulam, focusing on using sugi, can meet the required standards and thus be used in house construction.[3] Part of this research was to create sugi glulam using extremely low Young's modulus laminae (3–5 kN/mm^2) in the inner layers. The production of sugi with a relatively low Young's modulus has been increasing, especially in southern Japan because of its mild and humid climate, so we needed to find how this kind of sugi can be effectively used. Measurements were carried out and the mechanical properties of the glulam were recorded.[4,5] Armed with this new data, the researchers petitioned the Forestry Agency to amend the JAS to include

extremely low Young's modulus laminae (3–5 kN/mm^2) for the inner members of glulam. The agency accepted the researchers' argument and recently amended the JAS for glulam to reflect the new findings. However, the next stage of research mandates long-term behavior tests to determine how this kind of glulam can be used. In particular, it is important to estimate the relative creep in 50 years based on experiments and to compare this value with that stipulated by Notification No. 1459 of the Ministry of Construction in Japan, and thus to ascertain the potential of the glulam for usage as beams. In addition, the fact that there have been few reports on this sort of experiment using several kinds of glulam with different compositions[6] and real-sized sections is an issue that should be resolved promptly.

Bending creep tests on sugi glulam with extremely low Young's modulus laminae for the inner layers, along with tests on hybrid composite glulam with Douglas-fir (*Pseudotsuga menziesii* Franco) laminae for the outermost layer and the sugi laminae with extremely low Young's modulus for the inner layers, were carried out over a period of 4 years. In this report, the tendencies of bending creep, the estimation of the creep curve, and the variation of Young's modulus with respect to the composition of the laminae, which was carried out in advance, are discussed.

Materials and methods

Specimens

For the tests, glulam beams with eight different compositions and with dimensions of 105 mm in width, 210 mm in depth, and 3980 mm in length were prepared (See Fig. 1). Six are composed of sugi laminae only, and the other two beams are hybrid glulam composed of sugi laminae for the inner layers and Douglas-fir laminae with a Young's modulus of 14–15 kN/mm^2 (L140) for the outermost layers. Two of the six sugi glulam beams and the two hybrid glulam beams were symmetric and had laminae with a Young's modulus of 5–6 kN/mm^2 (L50) or 3–4 kN/mm^2 (L30) for the inner layers. These are called Sugi L50, Sugi L30, Hybrid L50, and Hybrid L30. The other four of the six sugi glulam beams were asymmetric and also had L50 or L30 for the inner layers. Those containing L50 are called Sugi LH-L50 and Sugi HL-L50, and those containing L30 are called Sugi LH-L30 and Sugi HL-L30. At the same time, these asymmetric beams are also classified into two groups according to the loading direction, i.e., Sugi LH-L30 and Sugi LH-L50 are loaded from the side with the lower Young's modulus, and Sugi HL-L30 and Sugi HL-L50 are loaded from the side with the higher Young's modulus. These two groups are termed the Sugi LH group and the Sugi HL group for simplicity. The details of the cross sections of the various glulam compositions are shown in Fig. 1, and the properties of the specimens are shown in Table 1.

Bending creep test

Bending creep tests were carried out for 4 years (October 12, 2005 to October 13, 2009) under four-point loading conditions with span lengths of 3655 mm, shear span lengths of 1260 mm, and a load span length of 1135 mm (See Fig. 2). The applied load was calculated based on a beam in the

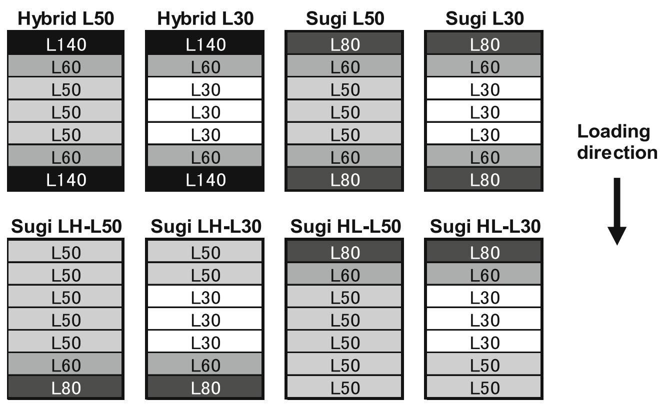


Fig. 1. Cross sections of glulam made from different grades of laminae. The thickness of the laminae was 30 mm and the dimensions of the glulam were 105 × 210 × 3980 mm. The adhesive was resorcinol resin. *L140*, Douglas-fir laminae; *L30–L80*, sugi laminae

Table 1. Properties of glued laminated timber (glulam)

Classification	Composition	Density (g/cm^3)		MC_r (%)		MC_0 (%)	MOE (kN/mm^2)		MOR (N/mm^2)
		Initial state	4 years later	Initial state	4 years later	4 years later	Initial state	4 years later	4 years later
Hybrid L50	Symmetric	0.447	0.438	16.0	13.5	11.1	10.6	11.2	59.8
Hybrid L30		0.448	0.447	14.8	13.5	11.9	10.8	11.5	51.2
Sugi L50		0.463	0.462	14.3	13.0	11.7	7.10	7.69	44.9
Sugi L30		0.409	0.410	16.3	14.2	11.4	6.83	7.41	30.1
Sugi LH-L50	Asymmetric	0.446	0.445	9.80	10.5	11.6	5.22	6.09	28.5
Sugi LH-L30		0.421	0.421	12.3	13.2	11.4	5.45	6.05	53.9
Sugi HL-L50		0.415	0.415	17.0	18.8	11.4	5.34	5.64	37.3
Sugi HL-L30		0.431	0.429	10.5	15.0	11.4	5.36	5.83	32.5

MC_r, moisture content measured by radio-frequency type moisture meter; MC_0, moisture content measured by oven drying method; MOE, Young's modulus in bending; MOR, modulus of rupture in bending

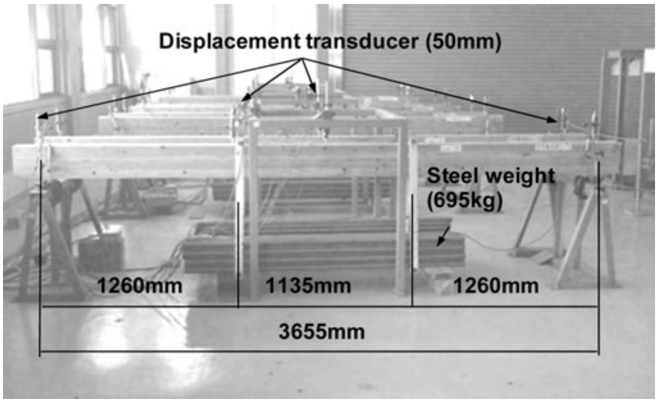


Fig. 2. Experimental conditions for creep tests

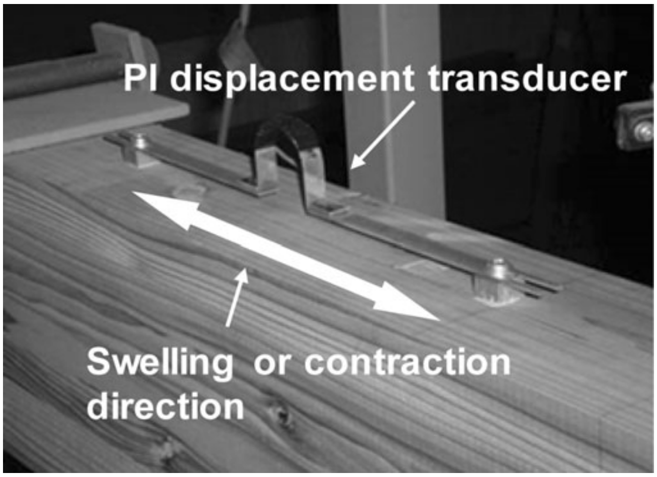


Fig. 3. PI displacement transducers set up on the specimens' top and bottom surfaces

second floor of two-story general wooden house. Specifically, the load per unit area was taken to be 190 kgf/cm^2 (dead load 60 kgf/cm^2 + live load 130 kgf/cm^2), then the total load per beam of 695 kgf was calculated. This calculation method was based on the Order for Enforcement of the Building Standards Law in Japan.

The displacement was measured at 24-h intervals via a data logger and displacement transducers (stroke: 50 mm) set at the center, near one of the load points, and at a supporting point on the beams. Along with these measurements, temperature and humidity were measured at the same intervals. In addition, to check the displacement in the grain direction on the compressive and the tensile sides of the beams, displacement transducers combined with strain gauges and an arch-shaped spring plate (PI displacement transducer, stroke: 300 mm) were put on the top and bottom at the center of beams, and measurements were taken at 1-h intervals (see Fig. 3). Measurement commenced on February 4, 2009.

Before the above creep tests were carried out, the effects of composition of laminae and loading direction on the bending Young's modulus were examined under the same span conditions to compare the tendencies between short-term and long-term deformation.

Results and discussion

Effects of composition of laminae and loading direction on bending Young's modulus

Figure 4 shows relationships between the bending Young's modulus when the glulam was loaded from the side of lower Young's modulus (MOE-LH) and from the side of higher Young's modulus (MOE-HL). Here, the data for glulam with symmetric compositions (Sugi L30, L50 and Hybrid L30, L50) are also plotted to allow easy comparison.

There are almost no differences between the values of MOE-LH and MOE-HL for the asymmetric glulam, and the composition of the laminae (symmetric or asymmetric) also had little effect. Considering this result and the fact that the modulus of rupture in bending (MOR) of the Sugi-LH and Sugi-HL groups does not show clear superiority in either loading direction (See Table 1), it may be unnecessary to consider loading direction with respect to the layer directions of laminae when glulam is installed as a structural member, at least for short-term considerations.

Figure 4 also shows that the MOEs of Hybrid L50 and L30 are clearly higher than the others. This result indicates that the bending Young's modulus of glulam greatly depends on the properties of the outermost layer, i.e., it is effective to place laminae with higher Young's modulus in the outermost layer to control short-term deflections. In addition, Fig. 4 shows that the MOEs of glulam with L30 and L50 for the inner layers are fairly similar.

Effects of composition of laminae and loading direction on bending creep

Figures 5 and 6 show the deflection changes and relative creep, respectively, with loading time. On the whole, the creep curves in these graphs show the general tendencies of primary and secondary creep. However, these curves are not necessarily smooth; in fact some are quite rough (see Fig. 6). The smoothest curves are those of Hybrid L30 and Sugi L30. The short-term deviations in the curves are considered to be mechanosorptive deflection[7] because the curves clearly follow humidity changes (see Fig. 7). In particular, the creep increase from the rainy season (June) to summer (August) is conspicuous for all specimens.

As for the extent of deflections in Fig. 5, the highest values were for the sugi asymmetric composition, followed by the sugi symmetric composition and hybrid glulam; clear differences were evident for each type. These tendencies are as predicted, considering the Young's modulus of the laminae of each glulam. In contrast, there were no conspicuous differences among the eight glulam configurations for relative creep in Fig. 6, at least in terms of creep increase; however, the tendency of Sugi L30 was a little more stable than the others.

In both Figs. 5 and 6, the deflections and relative creep are not very different for glulam with L30 and L50 for the inner layers, as was the case for the MOEs shown in Fig. 4. These results show that there is no practical problem in

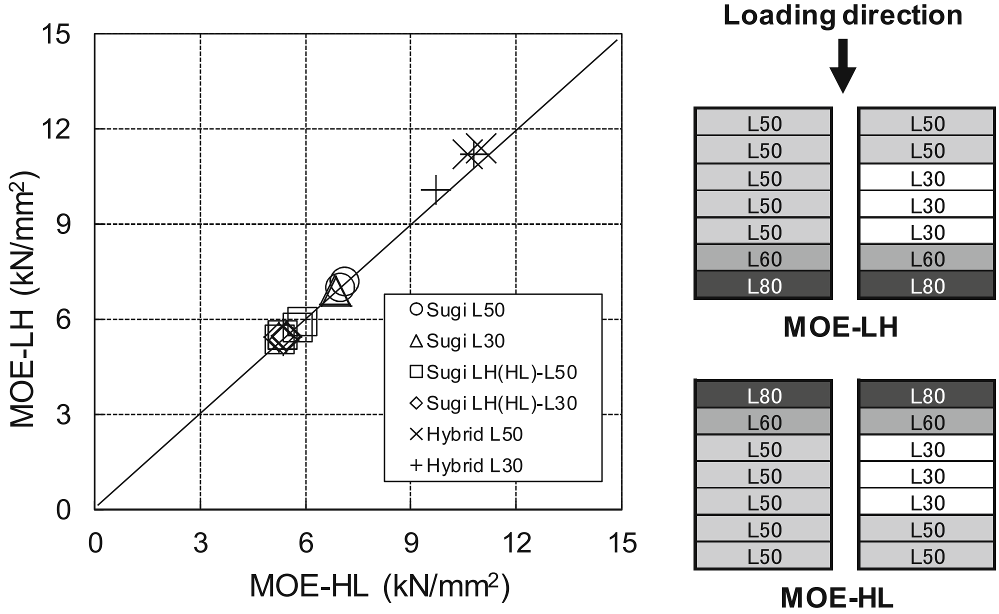


Fig. 4. Relationships between the bending Young's moduli when the glulam was loaded from the side with the lower Young's modulus (*MOE-LH*) and from the side with the higher Young's modulus (*MOE-HL*). Data for symmetric glulam (○Δ×+) are also shown for comparison

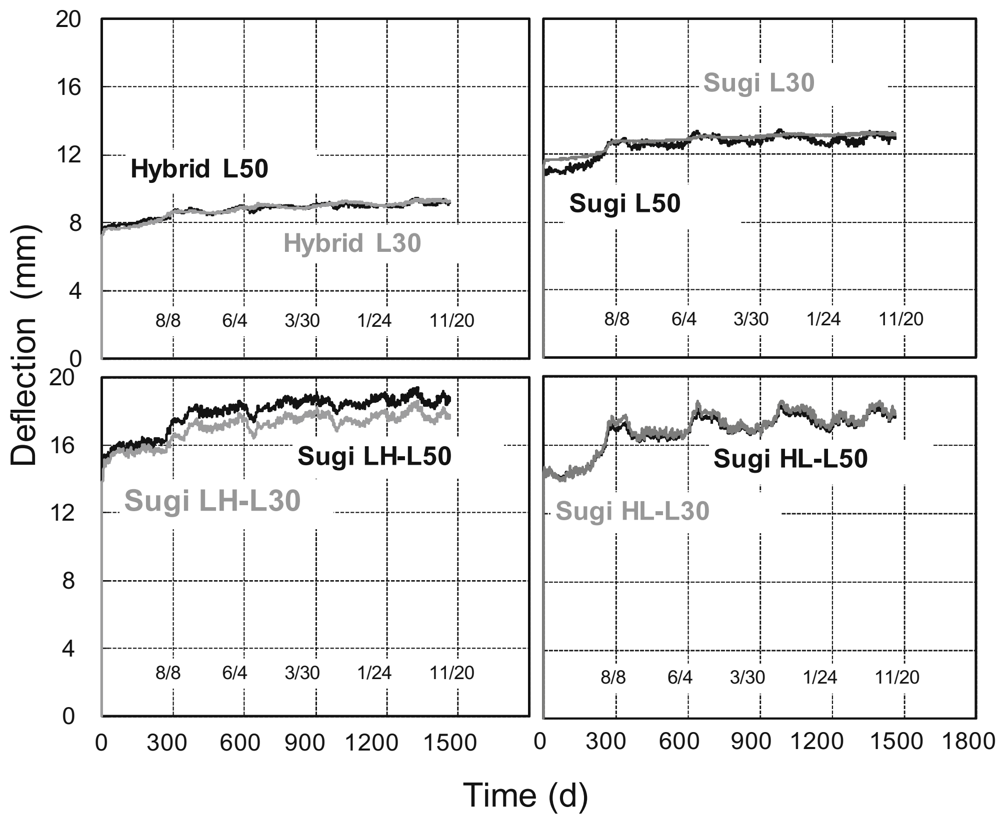


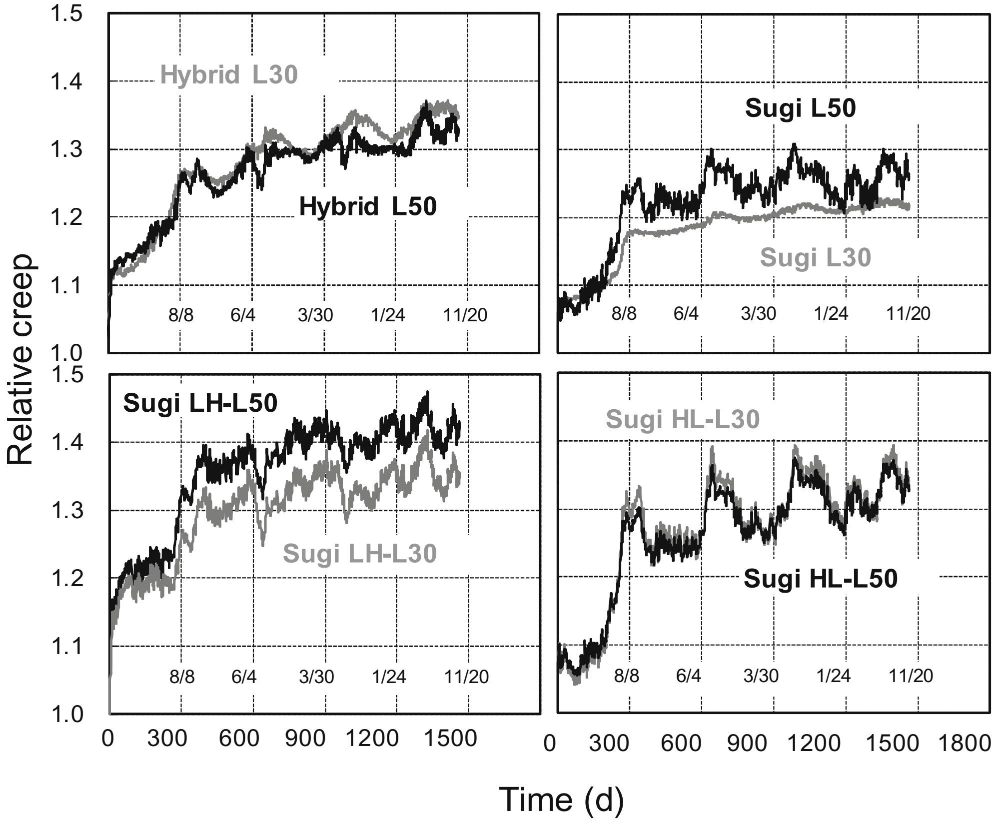
Fig. 5. Deflection changes with loading time. *8/8* and others show the month and date

using laminae with an extremely low Young's modulus, e.g., L30, for the inner layers not only in the short term, but also in the long term.

Incidentally, the lower two graphs in Fig. 6 show that the changes in relative creep between the Sugi LH group and the Sugi HL group are out of phase. This must occur because the creep recovery and increase for the Sugi LH group correspond closely to the humidity levels, while the totally opposite behavior occurs in the Sugi HL group, as is confirmed in the right four graphs in Fig. 8. In contrast, no clear difference of tendency is recognized for the symmetric glulam compositions (Sugi L50, L30 and Hybrid L50, L30) in the left four graphs.[8]

To look into what causes this pattern of change in the asymmetric glulam, PI displacement transducers were placed on the top and the bottom at the center of beams.

Fig. 6. Changes in relative creep with loading time



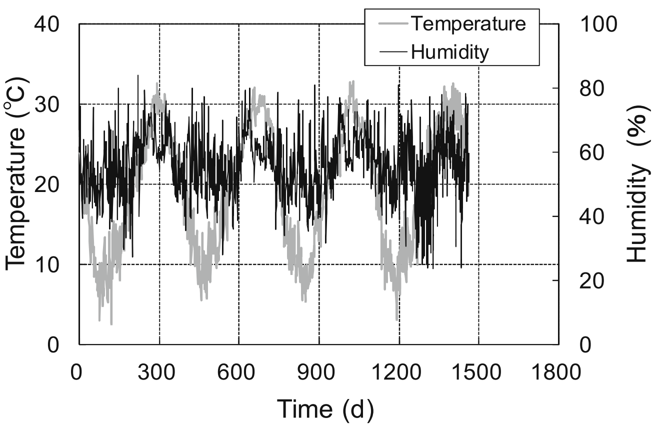


Fig. 7. Changes in temperature and humidity

Then the displacement in the grain direction (swelling or contraction) was measured (see Fig. 3).

Figure 9 shows changes of displacement in the grain direction on the top and bottom at the center of beams, as measured by PI displacement transducers, and the relative creep of the glulam. As shown in the upper two graphs in this figure, the displacement increases or decreases with the temperature and humidity changes (See Fig. 7). In this case, it is clearly recognized that the response of the lower Young's modulus side (L50 side) is much more marked than that of the higher Young's modulus side (L80 side), especially during temperature and humidity increases. This must be caused by the difference in properties between the outermost laminae. To put it concretely, laminae with lower Young's modulus values tend to have a relatively steep grain angle, which means their swelling or contraction in the grain direction during temperature and humidity changes can be more marked than that in laminae with higher Young's modulus. The deflection changes of the whole glulam seem to be strongly influenced by the behavior of these laminae placed in the outermost layer. In other words, when the outermost laminae with lower Young's moduli swell or contract in the longitudinal direction, the whole glulam can be deformed in that particular direction, as shown in the lower two graphs in Fig. 9. This explains the peculiar tendencies in the lower two graphs in Fig. 6.

These results show that the response of deflection to atmospheric changes was mainly influenced by the composition of the laminae, especially the properties of the outermost laminae. Also, the relation between lamina composition and loading direction should be considered, especially when asymmetric glulam is used as a beam.

Estimation of bending creep

Effect of experimental term

It is well known that the creep curve of wood and wood-based materials, especially real-sized samples, conforms relatively well with a power law relationship.[9–11] Therefore, the design values of relative creep in 50 years calculated with this equation are adopted in the Standard for Structural Design of Timber Structures issued by the Architec-

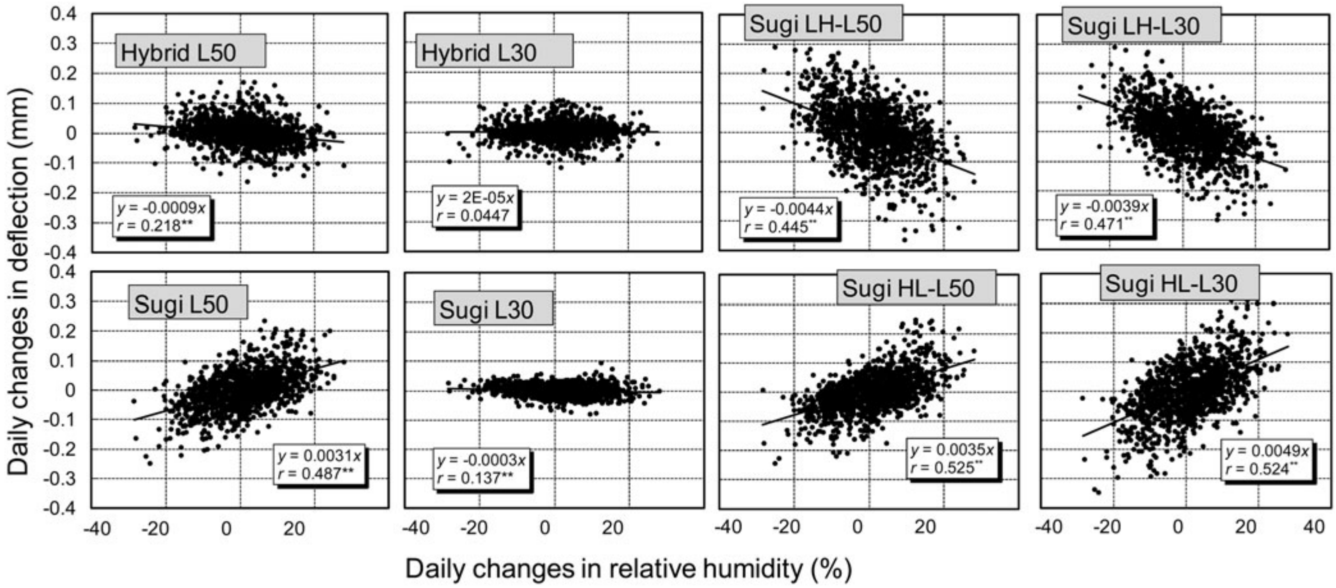


Fig. 8. Relationships between deflection changes per day and humidity changes per day

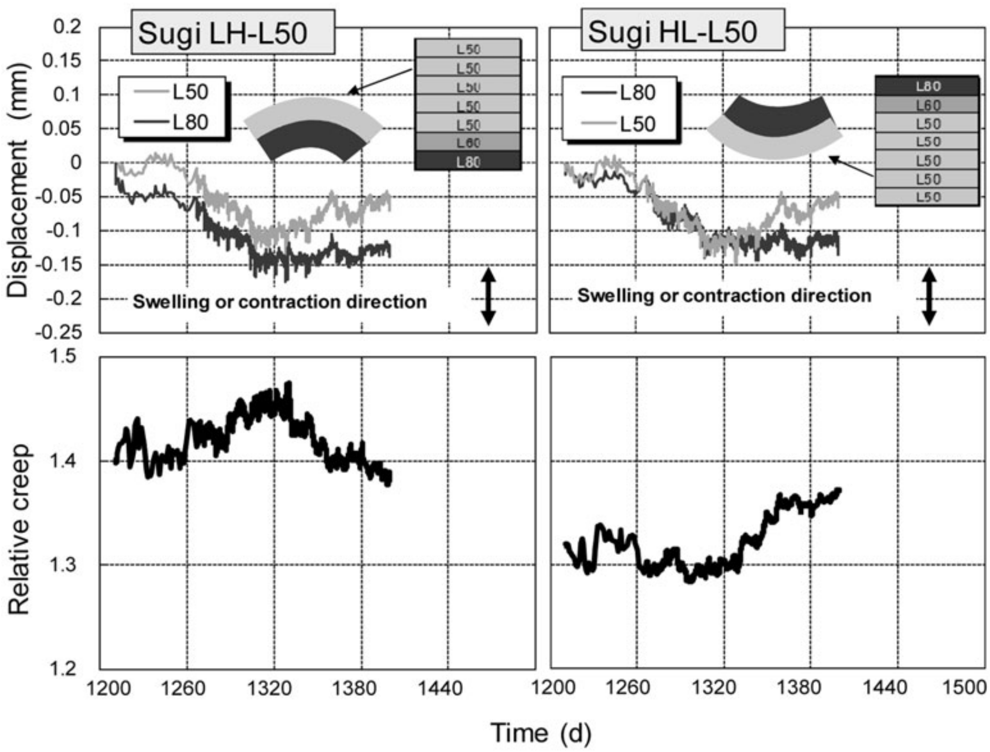


Fig. 9. Displacement in the grain direction on the top and bottom at the center of the beams and the relative creep of the glulam

tural Institute of Japan,[12] a standard that is widely used by Japanese architects and designers. Based on this background, a power law was chosen to estimate each creep curve in this study; in addition, the method based on the creep adjustment factor, which obtains the creep constants by linear regression analysis, could also be effective.[13]

Figure 10 shows comparisons between actual creep deflections and creep deflections calculated by applying the power law [$\delta_c(t)$] for two measurement periods, i.e., 3 months and 4 years:

$$\delta_c(t) = At^N \tag{1}$$

where the constants A and N, which are called the creep constant and deceleration exponential, respectively[14], were obtained from the curves from the start of the experiment to each measuring term (3 months or 4 years).

As shown in Fig. 10, creep curves estimated based on the short-term measurement (3 months) were not very accurate, especially in the case of asymmetric glulam shown in the right four graphs. On the other hand, relatively accurate

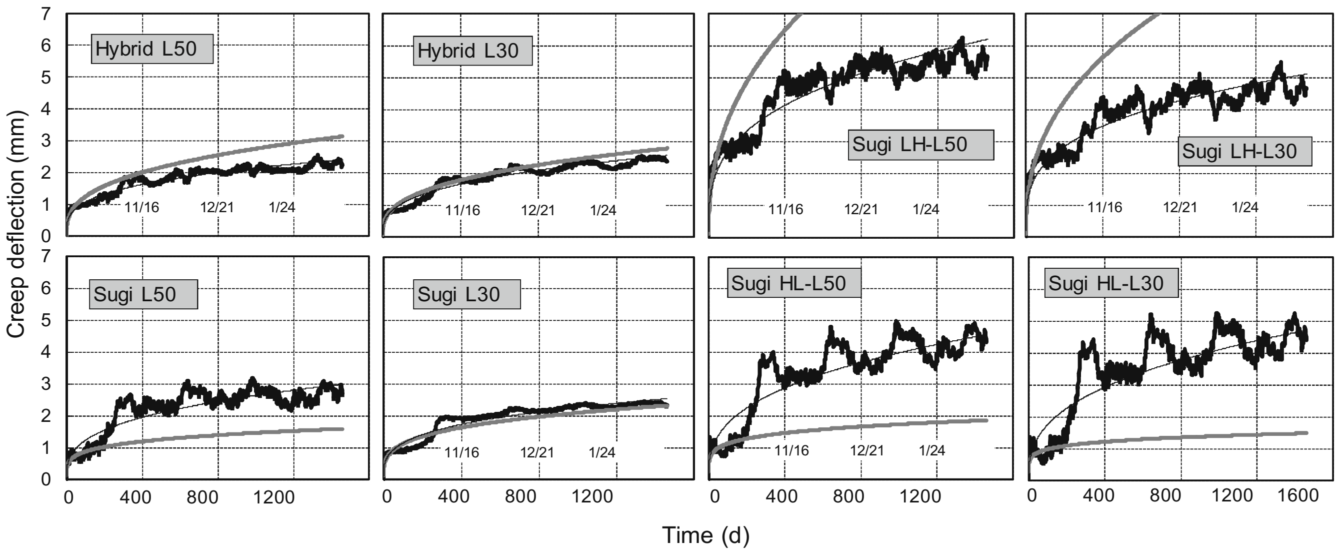
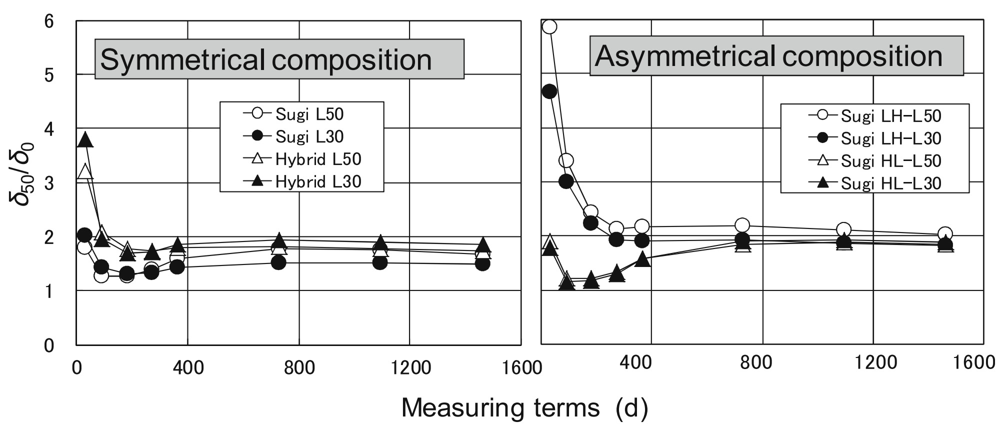


Fig. 10. The actual creep deflections and creep deflections calculated using the power law with constants derived using two measuring terms. *Thick black line*, actual values; *gray line*, values calculated using the power law derived from 3 months of measured data; *thin black line*, values calculated using the power law derived from 4 years of measured data. Constants A and N in the power law were obtained from the curves from day 1 to the end of each measuring term

Fig. 11. Relative creep in 50 years (δ_{50}/δ_0) calculated using Eq. 2 based on the power law derived from data for several measuring terms. Constants A and N in the power law were obtained by using the curves from day 1 to the end of each measuring term (1, 3, 6, and 9 months and 1, 2, 3, and 4 years)



calculated curves were obtained using the power law constants estimated using the long-term measurement period (4 years), regardless of the type of glulam.

This result shows that a required experimental term, which may depend on the composition of the laminae and the loading direction, should be clarified to estimate creep curves as efficiently and accurately as possible.

The increases and decreases of the creep deflections resulting from changes in temperature and humidity are not evident when the creep curves are estimated using the power law, so it seems that atmospheric changes do not strongly influence the rough estimation of long-term creep curves as far as it can be judged from Fig. 10. Besides, taking atmospheric conditions into consideration may not be practical for estimating creep curves as data are unlikely to be recorded for many years on site.

Based on these findings, the required experimental term to accurately estimate the relative creep in 50 years (δ_{50}/δ_0) was examined. Figure 11 shows δ_{50}/δ_0 values calculated using the following equation, which is based on the power law (Eq. 1), with constants estimated from data covering several measuring terms (1, 3, 6, and 9 months and 1, 2, 3, and 4 years):

$$\delta_{50}/\delta_0 = 1 + at^N \tag{2}$$

where δ_0 is the actual value of the initial deflection measured 30 min after commencement of loading, δ_{50} is the creep deflection in 50 years estimated by the power law, and a is A/δ_0, which is relative creep one day after loading. The time when δ_0 is taken has been discussed many times[11,15] and is still controversial in Japan since it directly effects δ_{50}/δ_0. Although the time should be just after the commencement of loading, such as 1 or 2 min, the deflection measured after 30 min of loading was chosen in this test, considering both the experimental conditions using real-sized lumber, which requires a long time to load, and the practical situations on site. In fact, the results of an examination carried out by the authors beforehand showed that there was no significant difference between the deflections measured at 1 min and at 30 min.

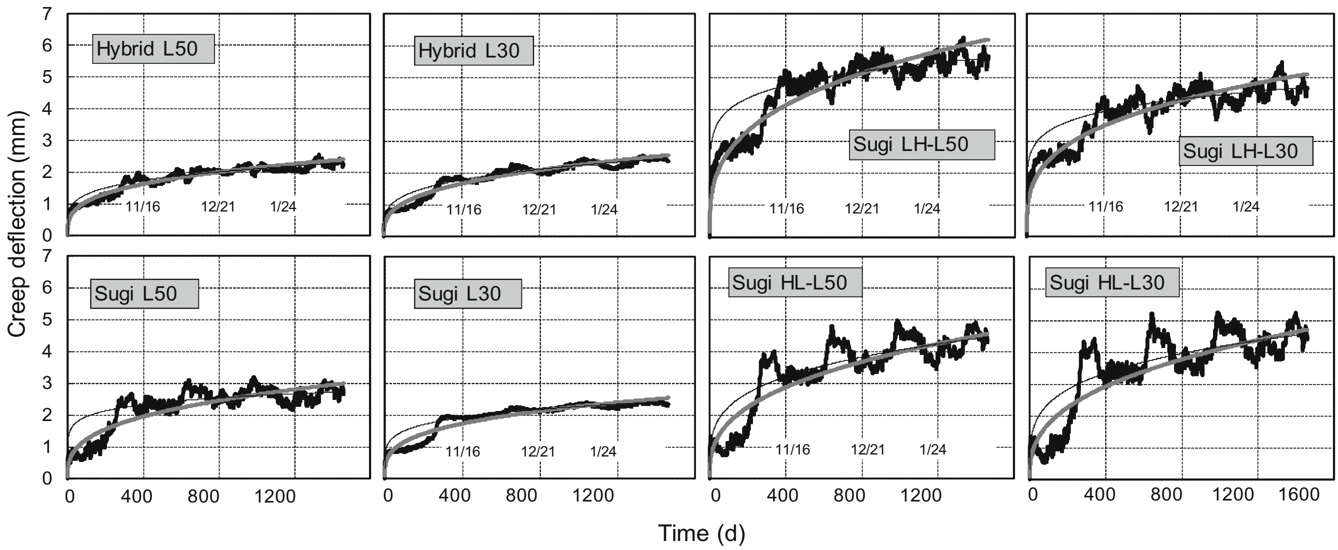


Fig. 12. Actual creep deflections and creep deflections calculated using the power law. *Thick black line*, actual values; *gray line*, calculated values obtained by using the curve from day 1 to year 4; *thin black line*, calculated values obtained by the curve from year 1 to year 4

Table 2. Power law constants for Eq. 2 estimated using data from three measuring terms representing different creep stages

Specimens	Constants for day 1 to year 4			Constants for month 6 to year 4			Constants for year 1 to year 4		
	$a = A/\delta_0$	N	δ_{50}/δ_0	$a = A/\delta_0$	N	δ_{50}/δ_0	$a = A/\delta_0$	N	δ_{50}/δ_0
Hybrid L50	0.0385	0.302	1.74	0.0505	0.261	1.65	0.0712	0.210	1.56
Hybrid L30	0.0329	0.333	1.86	0.0432	0.293	1.77	0.0587	0.248	1.67
Sugi L50	0.0259	0.331	1.67	0.0582	0.214	1.48	0.105	0.127	1.37
Sugi L30	0.0272	0.296	1.50	0.0327	0.270	1.46	0.0607	0.179	1.35
Sugi LH L50	0.0485	0.312	2.03	0.0687	0.258	1.86	0.168	0.127	1.59
Sugi LH L30	0.0444	0.298	1.82	0.0545	0.265	1.73	0.132	0.137	1.50
Sugi HL L50	0.0257	0.356	1.84	0.0384	0.302	1.74	0.0530	0.253	1.64
Sugi HL L30	0.0241	0.369	1.90	0.0407	0.297	1.75	0.0586	0.243	1.63

$a = A/\delta_0$, relative creep one day after loading; N, deceleration exponential; δ_{50}/δ_0, relative creep in 50 years

As shown in Fig. 11, δ_{50}/δ_0 becomes rather stable when the measuring terms are, on the whole, longer than 1 year for symmetric glulam compositions, as has been reported previously,[16] and 2 years for asymmetric glulam. The stable values of δ_{50}/δ_0 were approximately 2, which is the standard value set by Notification No. 1459 of the Ministry of Construction in Japan. This result shows that the required experimental term is 1 or 2 years to obtain a reliable estimated value of δ_{50}/δ_0 when this method is used. In any case, the values of δ_{50}/δ_0 for glulam with L30 and L50 for the inner layers were not very different, as was the case for MOE (see Fig. 4).

Effect of applied creep stage for the estimation

While relatively accurate estimated curves were obtained with the long-term measurements, there is room for more accurate creep curves, since the estimated curves slightly overestimated the creep deflection in the latter half of the curves (See Fig. 10). This could be caused by including primary creep when the estimated curves were calculated, since creep curves are often unstable at the initial stage,[17] even though the specimens used were in the air dried condition with almost no mechanosorptive deflections in the process of desorption (drying process).[7] Therefore, in this section, the appropriate initial period for which data should be excluded when estimating the power law constants is examined to obtain more accurate values of δ_{50}/δ_0.

Figure 12 shows the actual creep deflections and the creep deflections calculated using the power law (Eq. 1) obtained by the actual curves from day 1 to 4 years and from 1 year to 4 years. The values of a (= A/δ_0), N, and δ_{50}/δ_0 obtained from these calculated curves and those from the curves from 6 months to 4 years are shown in Table 2.

As shown in Fig. 12, the calculated curves broadly accord with the actual curves, regardless of the type of glulam; the lines obtained by using the actual curves from day 1 to 4 years tend to overestimate the creep deflection in the latter half of the curves, as mentioned above for Fig. 10. This tendency is relatively marked for the Sugi LH group. On the other hand, what is evident from the values of δ_{50}/δ_0 in Table 2 is that the later the initial point chosen for the calculation, the smaller the values become regardless of the type of glulam. This result indicates that the creep stage data applied for estimation of the power law constants should be for

secondary creep.[18] It is suggested that data from the initial year of loading be excluded when δ_{50}/δ_0 is calculated, according to Table 2. In practice, excluding the first 6 months of data could be enough, considering the result obtained in the previous section, which concluded that the required experimental term is 1 or 2 years to obtain a reliable estimated value of δ_{50}/δ_0. This term (6 months) roughly coincides with that obtained from previous results as an appropriate term[19] for sugi lumber (105 mm in width and depth, 230 mm in length) processed by various drying methods.

These results show that the minimum creep testing term for real-sized glulam, especially beams, is 1 to 2 years, depending on the composition of the laminae (symmetric or asymmetric arrangement). It was also found that the initial 6 months of data should be excluded when estimating the power law constants. The δ_{50}/δ_0 values obtained from these suggested periods of data are much smaller than 2, which is the standard value set by Notification No. 1459 of the Ministry of Construction in Japan. In other words, the long-term performance of sugi glulam is within the safety limit for the Japanese standard for structural design. These results can be applied to glulam beams with either L30 or L50 laminae for the inner layers.

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